

SAND99-1478
Unlimited Release
Printed June 1999

Analysis of Subsidence Data for the Big Hill Site, Texas

Stephen J. Bauer
Underground Storage Technology

Sandia National Laboratories
P.O.Box 5800
Albuquerque, NM 87185-0706

ABSTRACT

The elevation change data measured at the Big Hill Strategic Petroleum Reserve (SPR) site over the last 10 years has been studied and a model utilized to project elevation changes into the future. The subsidence rate at Big Hill is low in comparison with other Strategic Petroleum Reserve sites and has decreased with time due to the maintenance of higher operating pressures and the normal decrease in creep closure rate of caverns with time. However, the subsidence at the site is projected to continue. A model was developed to project subsidence values 20 years into the future; no subsidence related issues are apparent from these projections.

TABLE OF CONTENTS

| | Page |
|--|-----------|
| ABSTRACT | 1 |
| TABLE OF CONTENTS | 2 |
| FIGURES | 3 |
| INTRODUCTION | 4 |
| RESULTS AND ANALYSES | 7 |
| DISCUSSION AND CONCLUSIONS | 13 |
| REFERENCES | 14 |
| APPENDIX 1: Measured and Projected Elevations at Big Hill | 15 |
| APPENDIX 2: Calculated Historical Subsidence Rates at Big Hill | 16 |
| APPENDIX 3: Fitting Parameters for Long Term Subsidence Prediction | 18 |
| DISTRIBUTION | 19 |

FIGURES

| Figure | Page |
|---|-------------|
| 1. Top of caprock contour map at Big Hill | 5 |
| 2. Big Hill salt dome structure map, including top of salt contours, shear zone and salt spine locations | 6 |
| 3. Big Hill site measured elevations (feet), April, 1989 | 7 |
| 4. Big Hill site measured elevations (feet), May, 1995 | 8 |
| 5. Big Hill site measured elevations (feet), January, 1999 | 8 |
| 6. Big Hill subsidence rate, 4/89-5/94 (ft/yr) | 9 |
| 7. Big Hill subsidence rate, 5/94-1/99 (ft/yr) | 9 |
| 8. Examples of exponential decay fit for stations “5” and “BH 114B” | 11 |
| 9. Big Hill site projected elevations (feet) for the year 2004 | 12 |
| 10. Big Hill site projected elevations (feet) for the year 2009 | 12 |
| 11. Big Hill site projected elevations (feet) for the year 2019 | 13 |

INTRODUCTION

The subsidence monument elevations at the Big Hill Strategic Petroleum Reserve (SPR) site have been surveyed nine times beginning in April, 1989. The earlier survey data has been most recently reported on by Osnes (1995). This report provides an update which includes additional measurements completed in the past few years. The changes in elevation, the rates of subsidence, as well as projections of future elevation changes are presented. Elevation data were most recently collected at the Big Hill site in January 1999. Data are used by the cavern engineer and other site personnel in assuring certain aspects of site integrity, for example how to plan for periodic inundation.

At Big Hill and other SPR sites in general, elevation changes are measured because they document surface subsidence resulting from creep closure of caverns. General subsidence on the scale of the site or portions thereof is seen in the survey data taken. This type of subsidence will capture gross effects of creep closure of underground openings in response to the state of stress in the salt surrounding the caverns. However, the measured long term subsidence provided by the surveys is important, especially because it permits the long term extrapolation of elevation changes into the future.

Elevation data represents the raw data. The most recent data set included 32 stations. The number of data points varies from year to year because it is a function of ability to find monuments, destruction of monuments, damage to monuments, etc. The measurements have been made at various time intervals; the current time interval is about two years.

In practice, measurements of subsidence are difficult at best. At Big Hill the reference is an off-site benchmark located close to the site (to the northwest of the DOE property). This introduces some small error in traversing the distance to the site. The leveling surveys are performed to Second-Order First-Class accuracy, with allowable vertical closure not to exceed approximately $0.025 \text{ ft}/\text{mile}^{0.5}$ (Osnes, 1995).

A layout of the site with cavern locations is given in Figure 1. This together with Figure 2 allows one to understand the impact (on the order of 1000 ft) of the thick caprock at Big Hill. It is likely that the thick caprock provides stability at the surface, even in the presence of subterranean creep closure of caverns. It is unclear exactly how the caprock's presence effects subsidence; its fracture and faulted condition is difficult to analyze. However, we know that the creep closure rate is on par with those at West Hackberry (Ehgartner, 1997) where the subsidence rate is much higher. For comparable cavern ages, the subsidence rate at West Hackberry was approximately 0.25 ft/yr (Bauer, 1997), whereas this study shows the Big Hill rate to be an order of magnitude less.

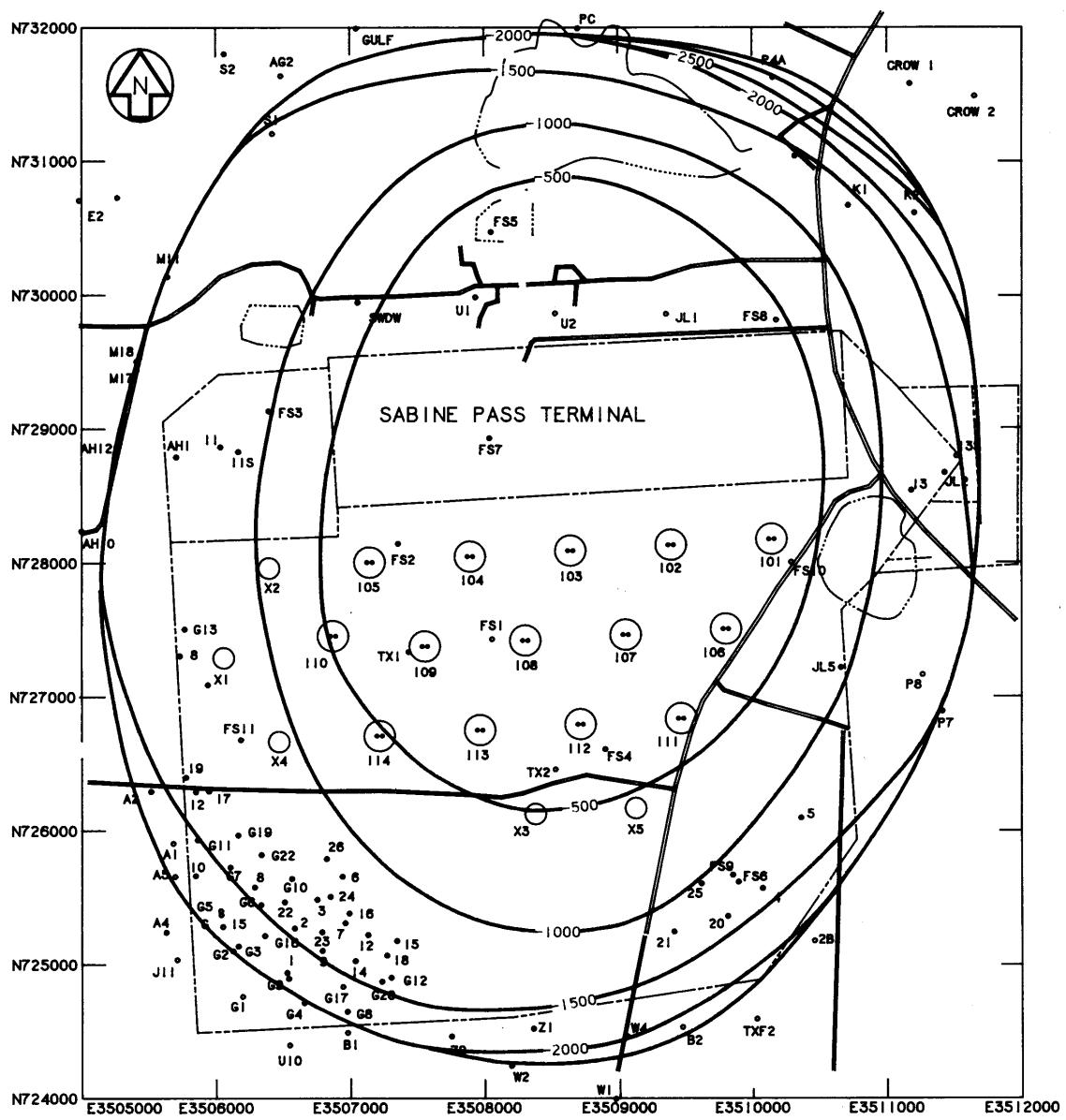


Figure 1. Top of cap rock contour map at Big Hill.

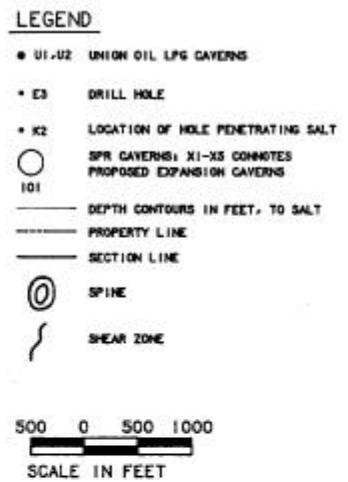
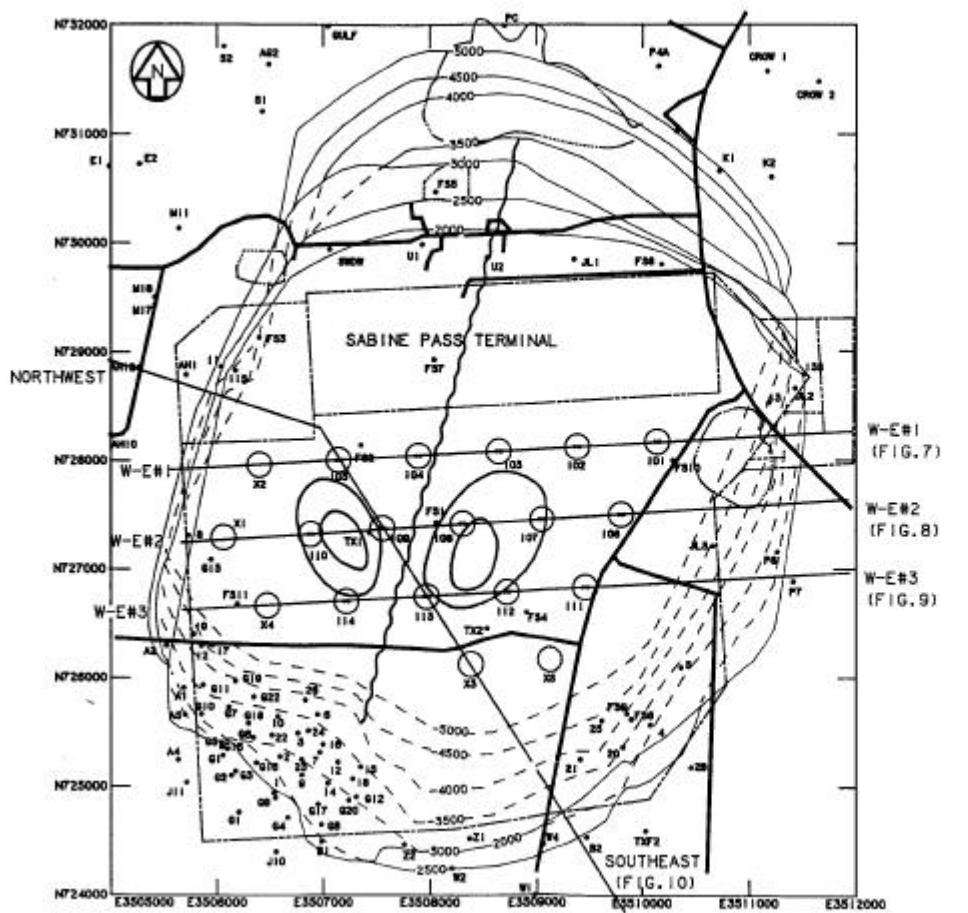


FIG. 1
BIG HILL SALT DOME
STRUCTURE MAP-SALT
SANDIA NATIONAL LABORATORIES
T.R. MAGORIAN
APRIL 1988

Figure 2. Big Hill salt dome structure map, including top of salt contours, shear zone and salt spine locations (Magorian and Neal, 1988).

RESULTS AND ANALYSES

As evidenced by the similarity between Figures 3-5, and data listed in Appendix 1, the elevation at the Big Hill SPR facility has changed very little during the past 10 years. The ground surface at the site has subsided on the average about 0.3 feet during the past 10 years. The data control (number of stations) is sparse at Big Hill. Most stations are located on well heads, thus the elevations reported are for well head elevations, not the ground level. This location of stations on well heads is common for SPR sites, because of the convenience. These elevations are known distances above the actual ground surface; their location does not effect the elevation change from measurement to measurement.

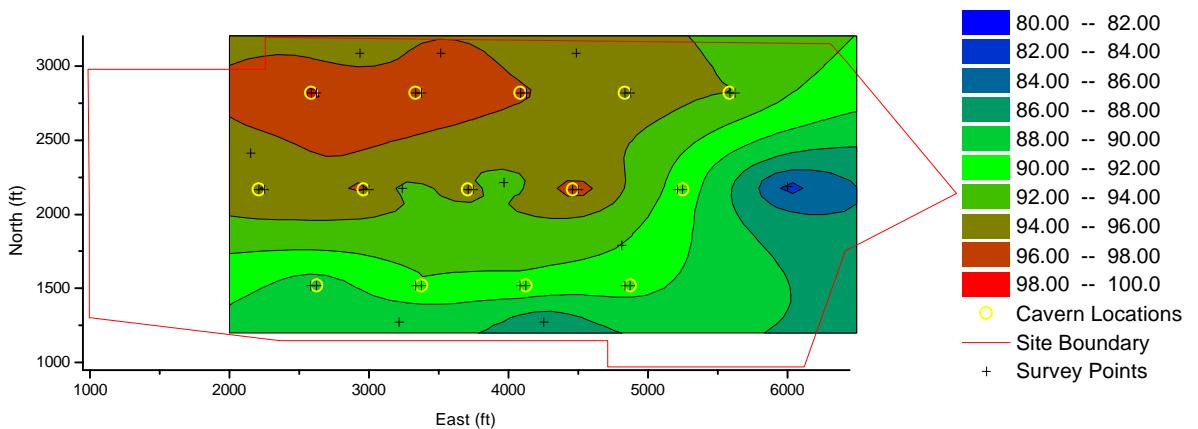


Figure 3. Big Hill site measured elevations (feet), April 1989.

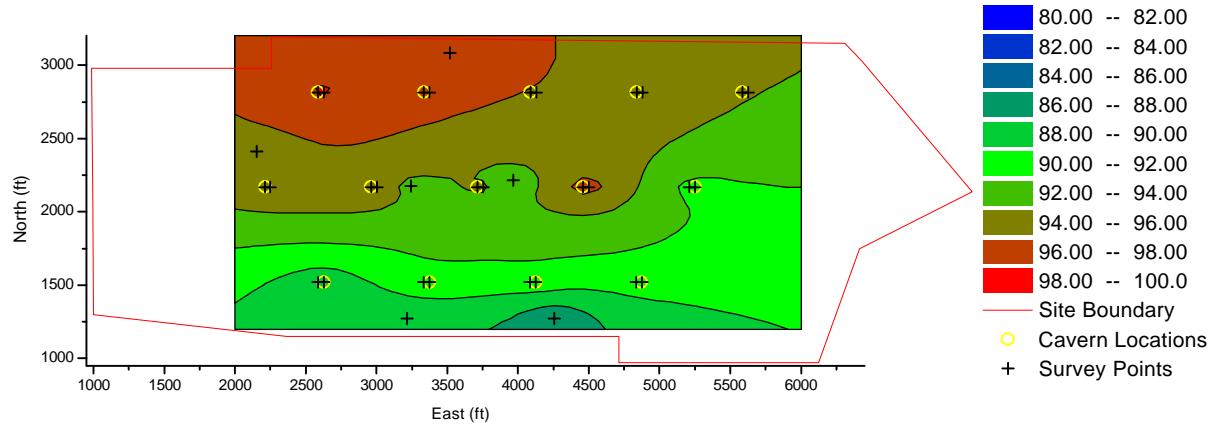


Figure 4. Big Hill site measured elevations (feet), May, 1995.

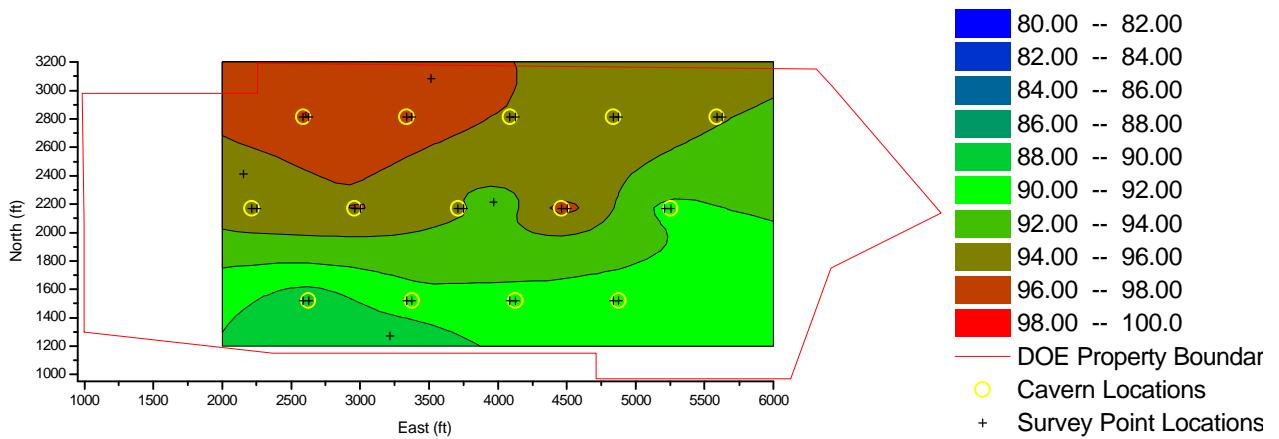


Figure 5. Big Hill site measured elevations (feet), January, 1999.

The rate of subsidence was studied to determine the uniformity of subsidence rates across the site. Local areas of greater subsidence rates may be signals of abnormal creep closure behavior, leaching of salt, and/or shifting of the caprock. The rate of subsidence is calculated by dividing the amount of elevation change in a time period by the time span of the period in years. This calculation was made for each time period between measurements and is presented in Appendix 2. The rate of subsidence has decreased during the measurement period. For the first five years of measurement the site was subsiding at about 0.02 to 0.05 feet per year (Figure 6); for the last five years the rate has decreased to 0.02 to 0.03 feet per year (Figure 7). This decrease is probably due to the operational procedure adopted of maintaining the caverns at relatively high operating pressure and the corresponding decrease in creep closure rate of the caverns with time. Transient creep effects are also diminishing with time (Ehgartner, 1992) since the earlier data reflects a time just after leaching (1990-1991).

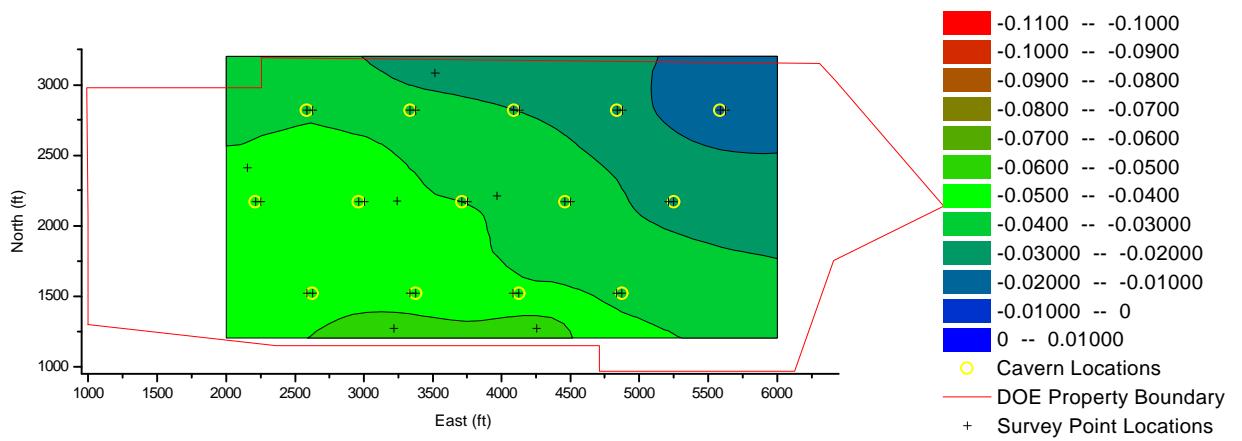


Figure 6. Big Hill subsidence rate, 4/89-5/94 (ft/yr).

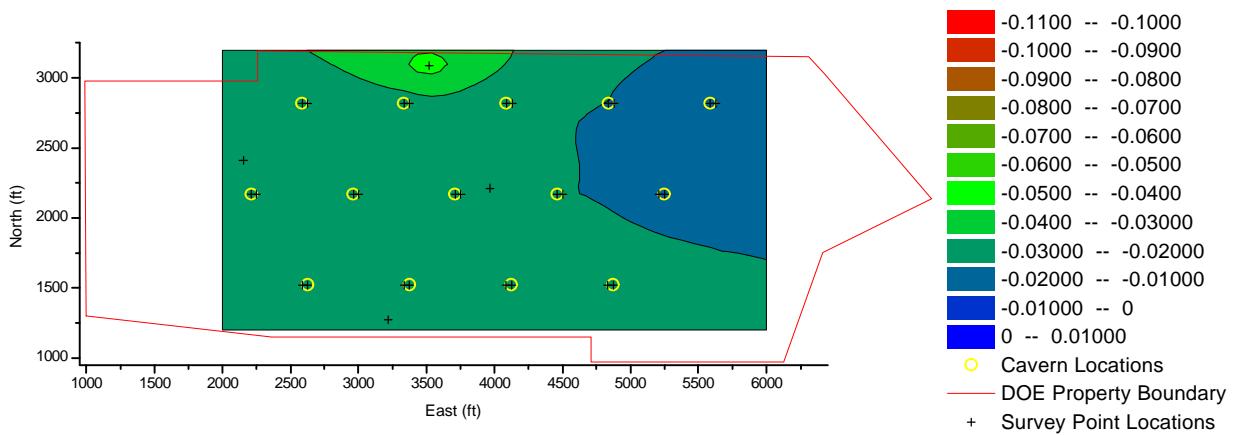


Figure 7. Big Hill subsidence rate, 5/94-1/99 (ft/yr).

It is important to develop a relationship to extrapolate changes in elevation into the future, in order to provide the DOE with important information for planning future work at the site. Such an extrapolation is possible by making use of the past history of the elevation measurements. Elevation data collected at known times at each station were fit to a first order exponential decay of the form:

$$Y = Y_0 + A_1 e^{-(x-x_0)/t_1}$$

where Y is the calculated elevation at the time of interest (x), Y_0 is the elevation at X_0 (time=0), A_1 is a constant, and t_1 is a fitting parameter.

This relationship allowed the data to be projected into the future with confidence. Examples of the data compared to the first order exponential decay relationship are given in Figure 8. Appendix 3 contains fitting parameters for equations fit to data for each measurement station allowing the reader to make projections to any time in the future.

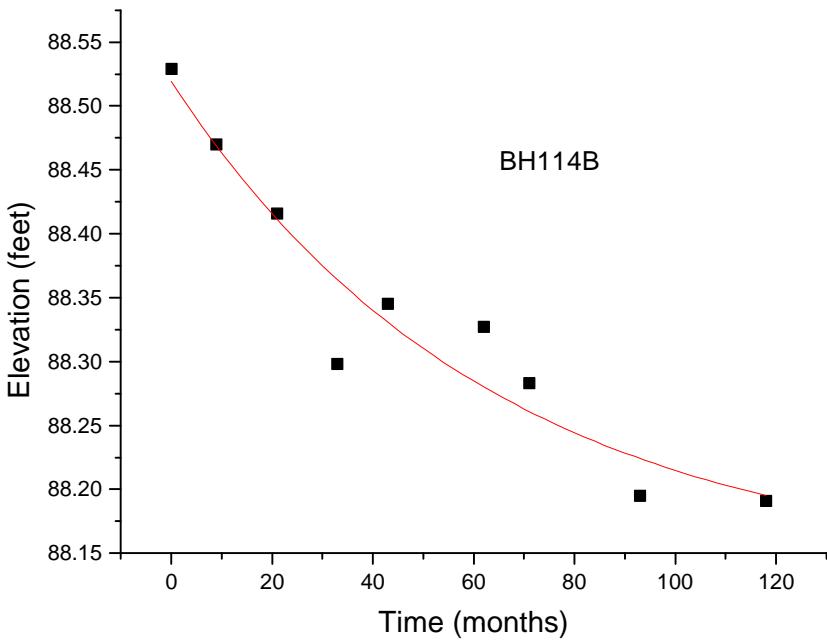
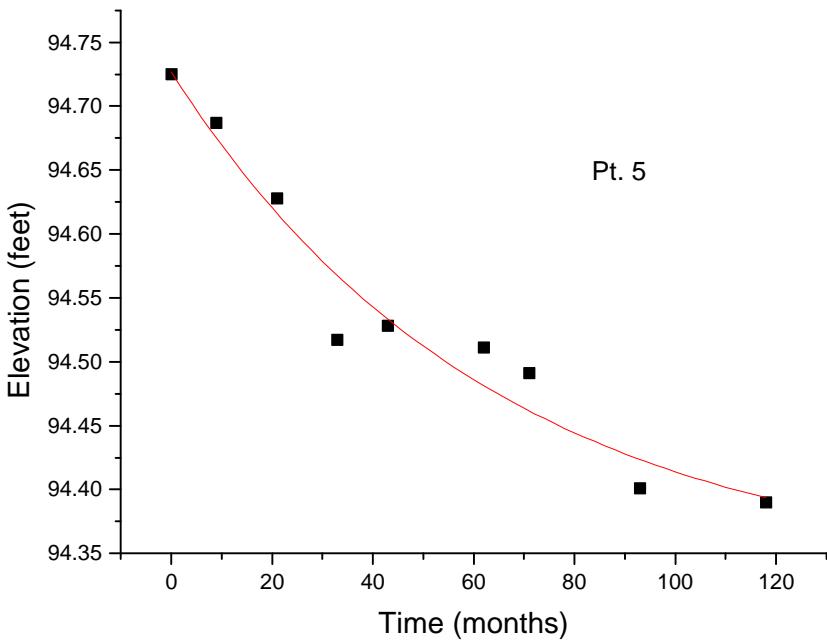


Figure 8. Examples of exponential decay fit for stations “5” and “BH 114B”.

Projected elevations for the years 2004, 2009, and 2019 are presented in Figures 9, 10, and 11. Consistent with information already presented, it is predicted that the Big Hill site will continue to subside, but at an ever decreasing rate.

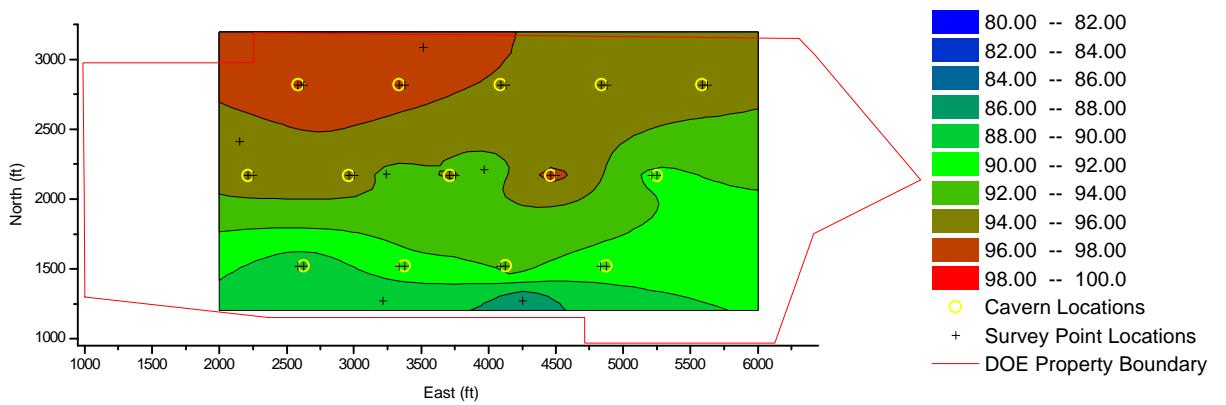


Figure 9. Big Hill site projected elevations (feet) for the year 2004. The contour interval is 2 feet.

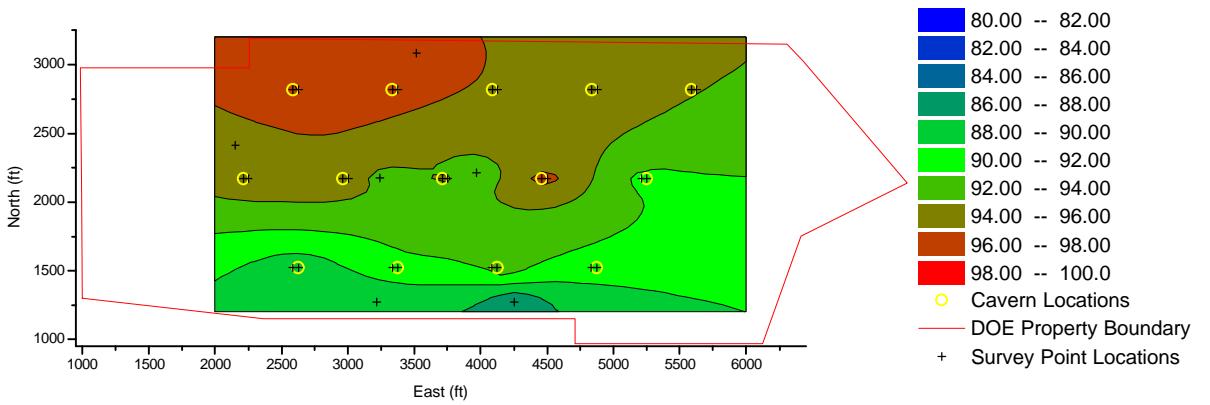


Figure 10. Big Hill site projected elevations (feet) for the year 2009. The contour interval is 2 feet.

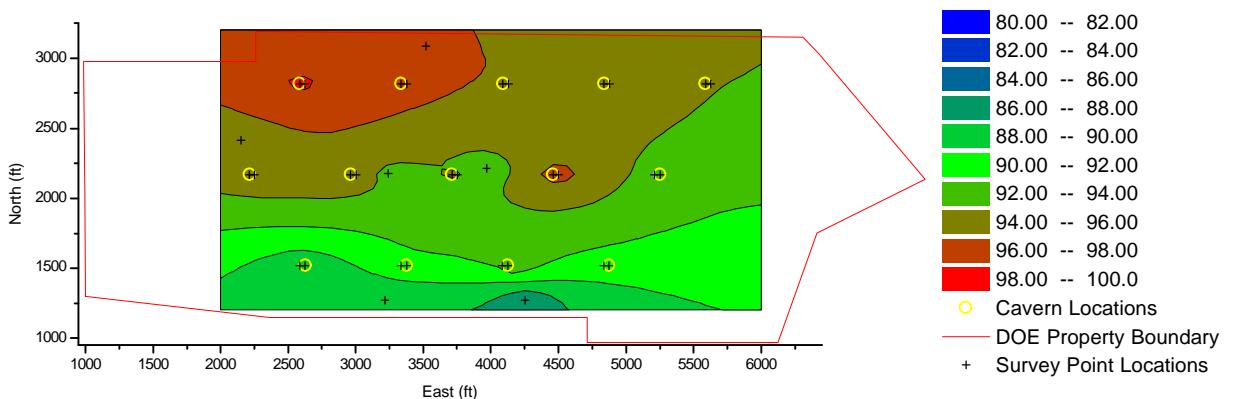


Figure 11. Big Hill site projected elevations (feet) for the year 2019. The contour interval is 2 feet.

DISCUSSION AND CONCLUSIONS

Big Hill is historically known for its low subsidence rates and relatively high elevations; this report echoes this historical perspective. No issues or concerns were uncovered in this analysis and review of historic and recent data.

The elevation change data at the Big Hill SPR site has been studied and a model utilized to project elevation changes 20 years into the future. This work may assist DOE in planning the construction and location of mitigative measures for operations as well as life extension.

Operationally it is prudent to continue the practice of maintaining the caverns at relatively high operating pressure. The measured subsidence rate is increased for time periods when higher cavern pressures were not maintained, and decreased for time periods when relatively high cavern pressures were maintained (this observation is more evident at older SPR sites that practiced a lower range in the operating pressure during the 1980's).

The results of analyses warrant the following conclusions:

- The subsidence rate has decreased with time due to relatively high operating pressures of caverns and the decrease in creep closure of caverns with time.
- The subsidence rate at Big Hill is low in comparison with other Strategic Petroleum Reserve sites; the subsidence at the site is projected to continue, however, if the cavern pressure is maintained at current levels, the subsidence rate can be expected to decrease.
- A model was developed to project subsidence values 20 years into the future; no subsidence related issues are apparent from these projections.

References

Bauer, S. J., 1997, "Analysis of Subsidence Data for the West Hackberry Site, Louisiana" SAND97-2036, Sandia National Laboratories, Albuquerque, NM.

Ehgartner, B., 1992, "Effects of Cavern Spacing and Pressure on Subsidence and Storage Losses for the U.S. Strategic Petroleum Reserve" SAND91-2575, Sandia National Laboratories, Albuquerque, NM.

Ehgartner, B., 1997, "SPR Ullage Study" SNL letter from Linn to Myers dated 11/25/97.

Osnes, J., 1995, "Update to subsidence analyses of SPR site for fiscal years 1993 and 1994," Re/Spec Topical Report RSI-0590 for DynMcdermott, published 3/95.

Magorian, T.R. and J. T. Neal, 1988, "Strategic Petroleum Reserve (SPR) Additional Geologic Site Characterization Studies Big Hill Salt Dome, Texas," SAND88-2267, September, 1988, Sandia National Laboratories.

Appendix 1

Measured and Projected Elevations at Big Hill

| Station | SUBSIDENCE MONITORING, (ft) | | | | | | | | | | | | | |
|-----------|-----------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|-----------|--------------|-----------|-------|-------|
| | APR 89 CONC | JAN 90 CONC | JAN 91 CONC | JAN 92 CONC | OCT 92 CONC | MAY 94 CONC | FEB 95 CONC | DEC 96 CONC | JAN 99 CONC | projected | projected | projected | | |
| RIEDEL | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | | |
| REF MON 2 | 76.78 | 76.78 | 76.78 | 76.78 | 76.78 | 76.78 | 76.78 | 76.78 | 76.78 | 76.78 | 76.78 | 76.78 | | |
| REF MON 4 | | | | | 96.82 | | | | | | | | | |
| | Time, months | 0 | 9 | 21 | 33 | 43 | 62 | 71 | 93 | 118 | projected | projected | | |
| | NORTH | EAST | APR 89 | JAN 90 | JAN 91 | JAN 92 | OCT 92 | MAY 94 | FEB 95 | DEC 96 | JAN 99 | 2004 | 2009 | 2019 |
| 5 | 2410.7 | 2154.8 | 94.73 | 94.69 | 94.63 | 94.52 | 94.53 | 94.51 | 94.49 | 94.40 | 94.39 | 94.36 | 94.34 | 94.33 |
| 6 | 3086.2 | 3516.4 | 96.90 | 96.87 | 96.87 | 96.81 | 96.81 | 96.82 | 96.82 | 96.76 | 96.60 | 96.53 | 96.41 | 96.18 |
| 7 | 3086.0 | 4486.4 | 94.44 | 94.41 | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A |
| 8 | 3085.1 | 2936.0 | 94.34 | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A |
| 9 | 1273.4 | 4256.3 | 85.30 | 85.26 | 85.20 | 85.04 | 85.02 | 85.01 | 85.01 | 84.91 | not found | 84.88 | 84.87 | 84.87 |
| 10 | 1273.3 | 3216.3 | 88.18 | 88.13 | 88.07 | 87.89 | 87.86 | 87.86 | 87.85 | 87.74 | 87.72 | 87.71 | 87.70 | 87.70 |
| 11A | 2187.0 | 6003.5 | 81.65 | 81.64 | 81.61 | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A |
| 12 | 1790.0 | 4814.7 | 92.08 | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A |
| 13 | 2175.8 | 3242.2 | 92.67 | 92.59 | 92.55 | #N/A | 92.44 | 92.46 | 92.42 | #N/A | #N/A | 92.40 | 92.40 | 92.40 |
| 14 | 2213.9 | 3968.4 | 91.72 | 91.67 | 91.60 | 91.51 | 91.52 | 91.52 | 91.50 | 91.40 | 91.40 | 91.39 | 91.38 | 91.38 |
| BH101A | 2817.0 | 5587.6 | 94.24 | 94.25 | 94.22 | 94.13 | 94.16 | 94.17 | 94.16 | 94.11 | 94.13 | 94.12 | 94.12 | 94.11 |
| BH101B | 2817.1 | 5627.3 | 94.17 | 94.18 | 94.14 | 94.06 | 94.10 | 94.10 | 94.10 | 94.05 | 94.07 | 96.06 | 94.06 | 94.06 |
| BH102A | 2816.8 | 4837.0 | 95.73 | 95.71 | 95.63 | 95.57 | 95.60 | 95.59 | 95.58 | 95.52 | 95.52 | 95.32 | 95.51 | 95.51 |
| BH102B | 2816.8 | 4877.0 | 95.67 | 95.67 | 95.59 | 95.52 | 95.56 | 95.55 | 95.53 | 95.47 | 95.47 | 95.47 | 95.47 | 95.46 |
| BH103A | 2817.0 | 4087.0 | 96.15 | 96.11 | 96.04 | 95.97 | 96.00 | 95.98 | 95.96 | 95.89 | 95.89 | 95.87 | 95.86 | 95.86 |
| BH103B | 2817.0 | 4127.3 | 96.16 | 96.12 | 96.06 | 95.98 | 96.00 | 95.99 | 95.97 | 95.90 | 95.88 | 95.85 | 95.84 | 95.83 |
| BH104A | 2816.9 | 3337.4 | 97.02 | 96.96 | 96.89 | 96.79 | 96.83 | 96.80 | 96.77 | 96.70 | 96.69 | 96.68 | 96.67 | 96.67 |
| BH104B | 2816.4 | 3377.4 | 97.14 | 97.09 | 97.00 | 96.91 | 96.96 | 96.92 | 96.90 | 96.83 | 96.79 | 96.78 | 96.77 | 96.77 |
| BH105A | 2816.8 | 2587.4 | 98.66 | 98.60 | 98.53 | 98.44 | 98.45 | 98.45 | 98.42 | 98.35 | 98.35 | 98.34 | 98.34 | 98.93 |
| BH105B | 2816.9 | 2626.9 | 98.67 | 98.62 | 98.55 | 98.45 | 98.47 | 98.46 | 98.46 | 98.37 | 98.36 | 98.36 | 98.36 | 98.36 |
| BH106A | 2167.9 | 5211.9 | 91.21 | 91.18 | 91.12 | 91.05 | 91.09 | 91.09 | 91.07 | 91.01 | 91 | 91.02 | 91.02 | 94 |
| BH106B | 2167.9 | 5251.7 | 91.23 | 91.20 | 91.14 | 91.07 | 91.08 | 91.09 | 91.07 | 91.01 | 91.02 | 91.02 | 91.02 | 91 |
| BH107A | 2167.9 | 4461.7 | 97.67 | 97.61 | 97.54 | 97.47 | 97.49 | 97.48 | 97.47 | #N/A | 97.39 | 97.41 | 97.41 | 97.41 |
| BH107B | 2167.9 | 4501.7 | 97.66 | 97.62 | 97.55 | 97.46 | 97.49 | 97.48 | 97.45 | 97.37 | 97.36 | 97.35 | 97.34 | 97.34 |
| BH108A | 2167.9 | 3711.7 | 94.69 | 94.63 | 94.54 | 94.44 | 94.49 | 94.47 | 94.42 | 94.34 | 94.3 | 94.34 | 94.34 | 94.34 |
| BH108B | 2167.9 | 3751.7 | 94.68 | 94.66 | 94.57 | 94.46 | 94.47 | 94.48 | 94.47 | 94.36 | 94.4 | 94.34 | 94.33 | 94.33 |
| BH109A | 2167.9 | 2961.7 | 96.59 | 96.54 | 96.47 | 96.35 | 96.38 | 96.36 | 96.34 | 96.24 | 96.25 | 96.23 | 96.22 | 96.22 |
| BH109B | 2167.9 | 3001.7 | 96.65 | 96.60 | 96.52 | 96.41 | 96.44 | 96.44 | 96.39 | 96.31 | 96.31 | 96.29 | 96.29 | 96.29 |
| BH110A | 2167.9 | 2211.7 | 96.13 | 96.10 | 96.03 | 95.93 | 95.96 | 95.94 | 95.92 | 95.82 | 95.81 | 95.78 | 95.77 | 95.76 |
| BH110B | 2167.9 | 2251.7 | 96.16 | 96.10 | 96.02 | 95.90 | 95.94 | 95.92 | 95.88 | 95.80 | 95.79 | 95.78 | 95.78 | 95.78 |
| BH111A | 1518.8 | 4876.1 | 91.17 | 91.13 | 91.06 | 90.97 | 91.01 | 91.00 | 91.02 | 90.92 | 90.88 | 90.91 | 90.90 | 90.90 |
| BH111B | 1518.6 | 4835.8 | 91.24 | 91.20 | 91.15 | 91.04 | 91.06 | 91.06 | 91.09 | 90.98 | 90.95 | 90.95 | 90.94 | 90.94 |
| BH112A | 1518.6 | 4126.1 | 91.68 | 91.64 | 91.57 | 91.46 | 91.47 | 91.47 | 91.47 | 91.38 | 91.34 | 96.23 | 96.22 | 96.22 |
| BH112B | 1518.3 | 4086.0 | 91.70 | 91.64 | 91.58 | 91.47 | 91.48 | 91.48 | 91.49 | 91.39 | 91.35 | 91.35 | 91.34 | 91.34 |
| BH113A | 1518.9 | 3376.3 | 92.18 | 92.12 | 92.07 | 91.94 | 91.96 | 91.96 | 91.94 | 91.85 | 91.82 | 91.81 | 91.80 | 91.79 |
| BH113B | 1518.7 | 3335.8 | 92.11 | 92.06 | 92.01 | 91.86 | 91.88 | 91.88 | 91.86 | 91.77 | 91.75 | 91.73 | 91.72 | 91.71 |
| BH114A | 1518.9 | 2625.6 | 88.37 | 88.30 | 88.24 | 88.11 | 88.16 | 88.14 | 88.10 | 88.01 | 88.00 | 87.98 | 87.98 | 87.97 |
| BH114B | 1518.8 | 2586.3 | 88.53 | 88.47 | 88.42 | 88.30 | 88.35 | 88.33 | 88.28 | 88.20 | 88.19 | 88.16 | 88.14 | 88.14 |

Appendix 2

Calculated Historical Subsidence Rates at Big Hill

Elevation change (ft); Interval rate (ft/yr)

| Station | NORTH | EAST | JAN 90 | | JAN 91 | | JAN 92 | | OCT 92 | | MAY 94 | |
|---------|--------|--------|--------|-------|--------|-------|--------|-------|--------|-------|--------|-------|
| | | | change | rate |
| 5 | 2410.7 | 2154.8 | -0.04 | -0.05 | -0.06 | -0.06 | -0.11 | -0.11 | 0.01 | 0.01 | -0.02 | -0.01 |
| 6 | 3086.2 | 3516.4 | -0.03 | -0.04 | 0.00 | 0.00 | -0.06 | -0.06 | 0.00 | 0.00 | 0.01 | 0.01 |
| 7 | 3086.0 | 4486.4 | -0.03 | -0.04 | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A |
| 8 | 3085.1 | 2936.0 | #N/A | #N/A |
| 9 | 1273.4 | 4256.3 | -0.05 | -0.06 | -0.05 | -0.05 | -0.16 | -0.16 | -0.03 | -0.03 | -0.01 | -0.01 |
| 10 | 1273.3 | 3216.3 | -0.05 | -0.07 | -0.06 | -0.06 | -0.18 | -0.18 | -0.04 | -0.04 | 0.01 | 0.00 |
| 11A | 2187.0 | 6003.5 | -0.02 | -0.02 | -0.03 | -0.03 | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A |
| 12 | 1790.0 | 4814.7 | #N/A | #N/A |
| 13 | 2175.8 | 3242.2 | -0.08 | -0.10 | -0.04 | -0.04 | #N/A | #N/A | #N/A | #N/A | 0.01 | 0.01 |
| 14 | 2213.9 | 3968.4 | -0.05 | -0.06 | -0.07 | -0.07 | -0.09 | -0.09 | 0.01 | 0.01 | 0.00 | 0.00 |
| BH101A | 2817.0 | 5587.6 | 0.01 | 0.01 | -0.03 | -0.03 | -0.09 | -0.09 | 0.03 | 0.04 | 0.01 | 0.00 |
| BH101B | 2817.1 | 5627.3 | 0.00 | 0.00 | -0.03 | -0.03 | -0.08 | -0.08 | 0.04 | 0.04 | 0.01 | 0.00 |
| BH102A | 2816.8 | 4837.0 | -0.02 | -0.03 | -0.08 | -0.08 | 0.06 | 0.06 | 0.03 | 0.03 | -0.01 | 0.00 |
| BH102B | 2816.8 | 4877.0 | -0.01 | -0.01 | -0.08 | -0.08 | -0.06 | -0.06 | 0.03 | 0.04 | -0.01 | -0.01 |
| BH103A | 2817.0 | 4087.0 | -0.04 | -0.05 | -0.07 | -0.07 | -0.07 | -0.07 | 0.02 | 0.03 | -0.02 | -0.01 |
| BH103B | 2817.0 | 4127.3 | -0.04 | -0.05 | -0.07 | -0.07 | -0.08 | -0.08 | 0.03 | 0.03 | -0.02 | -0.01 |
| BH104A | 2816.9 | 3337.4 | -0.06 | -0.08 | -0.08 | -0.08 | -0.09 | -0.09 | 0.04 | 0.05 | -0.03 | -0.02 |
| BH104B | 2816.4 | 3377.4 | -0.05 | -0.07 | -0.08 | -0.08 | -0.09 | -0.09 | 0.05 | 0.06 | -0.04 | -0.03 |
| BH105A | 2816.8 | 2587.4 | -0.05 | -0.07 | -0.07 | -0.07 | -0.09 | -0.09 | 0.01 | 0.01 | -0.01 | 0.00 |
| BH105B | 2816.9 | 2626.9 | -0.05 | -0.07 | -0.07 | -0.07 | -0.10 | -0.10 | 0.02 | 0.03 | -0.02 | -0.01 |
| BH106A | 2167.9 | 5211.9 | -0.03 | -0.04 | -0.06 | -0.06 | -0.07 | -0.07 | 0.04 | 0.04 | 0.01 | 0.00 |
| BH106B | 2167.9 | 5251.7 | -0.02 | -0.03 | -0.06 | -0.06 | -0.07 | -0.07 | 0.02 | 0.02 | 0.01 | 0.01 |
| BH107A | 2167.9 | 4461.7 | -0.06 | -0.08 | -0.07 | -0.07 | -0.08 | -0.08 | 0.03 | 0.03 | -0.01 | -0.01 |
| BH107B | 2167.9 | 4501.7 | -0.04 | -0.05 | -0.07 | -0.07 | -0.09 | -0.09 | 0.03 | 0.04 | -0.01 | -0.01 |
| BH108A | 2167.9 | 3711.7 | -0.07 | -0.09 | -0.09 | -0.09 | -0.10 | -0.10 | 0.05 | 0.06 | -0.02 | -0.01 |
| BH108B | 2167.9 | 3751.7 | -0.02 | -0.03 | -0.09 | -0.09 | -0.11 | -0.11 | 0.01 | 0.01 | 0.01 | 0.01 |
| BH109A | 2167.9 | 2961.7 | -0.05 | -0.07 | -0.07 | -0.07 | -0.11 | -0.11 | 0.02 | 0.03 | -0.02 | -0.01 |
| BH109B | 2167.9 | 3001.7 | -0.05 | -0.06 | -0.08 | -0.08 | -0.11 | -0.11 | 0.03 | 0.04 | 0.00 | 0.00 |
| BH110A | 2167.9 | 2211.7 | -0.03 | -0.04 | -0.08 | -0.08 | -0.10 | -0.10 | 0.03 | 0.04 | -0.02 | -0.01 |
| BH110B | 2167.9 | 2251.7 | -0.06 | -0.08 | -0.08 | -0.08 | -0.13 | -0.13 | 0.04 | 0.05 | -0.02 | -0.01 |
| BH111A | 1518.8 | 4876.1 | -0.03 | -0.05 | -0.07 | -0.07 | -0.09 | -0.09 | 0.04 | 0.05 | -0.01 | -0.01 |
| BH111B | 1518.6 | 4835.8 | -0.04 | -0.05 | -0.06 | -0.06 | -0.11 | -0.11 | 0.02 | 0.02 | 0.00 | 0.00 |
| BH112A | 1518.6 | 4126.1 | -0.05 | -0.06 | -0.06 | -0.06 | -0.11 | -0.11 | 0.01 | 0.02 | -0.01 | 0.00 |
| BH112B | 1518.3 | 4086.0 | -0.05 | -0.07 | -0.06 | -0.06 | -0.11 | -0.11 | 0.01 | 0.01 | 0.00 | 0.00 |
| BH113A | 1518.9 | 3376.3 | -0.06 | -0.07 | -0.05 | -0.05 | -0.13 | -0.13 | 0.02 | 0.03 | 0.00 | 0.00 |
| BH113B | 1518.7 | 3335.8 | -0.05 | -0.07 | -0.05 | -0.05 | -0.15 | -0.15 | 0.02 | 0.02 | 0.00 | 0.00 |
| BH114A | 1518.9 | 2625.6 | -0.06 | -0.09 | -0.06 | -0.06 | -0.12 | -0.12 | 0.04 | 0.05 | -0.02 | -0.01 |
| BH114B | 1518.8 | 2586.3 | -0.06 | -0.08 | -0.05 | -0.05 | -0.12 | -0.12 | 0.05 | 0.06 | -0.02 | -0.01 |

Appendix 2 (cont.)

Calculated Historical Subsidence Rates at Big Hill

Elevation change (ft); Interval rate (ft/yr)

| Station | NORTH | EAST | FEB 95 | | DEC 96 | | JAN 99 | | Total | |
|---------|--------|--------|--------|-------|--------|-------|-----------|-----------|--------|--------|
| | | | change | rate | change | rate | change | rate | change | rate |
| 5 | 2410.7 | 2154.8 | -0.02 | -0.03 | -0.09 | -0.09 | -0.01 | -0.01 | -0.33 | -0.03 |
| 6 | 3086.2 | 3516.4 | 0.00 | -0.01 | -0.05 | -0.05 | -0.16 | -0.08 | -0.30 | -0.03 |
| 7 | 3086.0 | 4486.4 | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A |
| 8 | 3085.1 | 2936.0 | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A |
| 9 | 1273.4 | 4256.3 | 0.00 | 0.00 | -0.10 | -0.10 | not found | not found | -0.39 | -0.04 |
| 10 | 1273.3 | 3216.3 | -0.02 | -0.02 | -0.10 | -0.10 | -0.02 | -0.01 | -0.46 | -0.05 |
| 11A | 2187.0 | 6003.5 | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A |
| 12 | 1790.0 | 4814.7 | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A |
| 13 | 2175.8 | 3242.2 | -0.03 | -0.05 | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A |
| 14 | 2213.9 | 3968.4 | -0.02 | -0.03 | -0.10 | -0.10 | 0.00 | 0.00 | -0.31 | -0.03 |
| BH101A | 2817.0 | 5587.6 | -0.01 | -0.01 | -0.04 | -0.04 | 0.02 | 0.01 | -0.11 | -0.01 |
| BH101B | 2817.1 | 5627.3 | -0.01 | -0.01 | -0.05 | -0.05 | 0.02 | 0.01 | -0.11 | -0.01 |
| BH102A | 2816.8 | 4837.0 | -0.02 | -0.03 | -0.05 | -0.05 | -0.01 | 0.00 | -0.21 | -0.02 |
| BH102B | 2816.8 | 4877.0 | -0.02 | -0.03 | -0.05 | -0.05 | 0.00 | 0.00 | -0.20 | -0.02 |
| BH103A | 2817.0 | 4087.0 | -0.02 | -0.03 | -0.07 | -0.07 | 0.00 | 0.00 | -0.27 | -0.03 |
| BH103B | 2817.0 | 4127.3 | -0.02 | -0.02 | -0.07 | -0.07 | -0.02 | -0.01 | -0.28 | -0.03 |
| BH104A | 2816.9 | 3337.4 | -0.03 | -0.03 | -0.07 | -0.07 | -0.01 | -0.01 | -0.33 | -0.03 |
| BH104B | 2816.4 | 3377.4 | -0.02 | -0.03 | -0.07 | -0.07 | -0.04 | -0.02 | -0.35 | -0.04 |
| BH105A | 2816.8 | 2587.4 | -0.02 | -0.03 | -0.08 | -0.08 | 0.00 | 0.00 | -0.31 | -0.03 |
| BH105B | 2816.9 | 2626.9 | 0.00 | 0.01 | -0.09 | -0.09 | -0.02 | -0.01 | -0.32 | -0.03 |
| BH106A | 2167.9 | 5211.9 | -0.02 | -0.03 | -0.06 | -0.06 | 0.00 | 0.00 | -0.20 | -0.02 |
| BH106B | 2167.9 | 5251.7 | -0.02 | -0.03 | -0.06 | -0.06 | 0.02 | 0.01 | -0.20 | -0.02 |
| BH107A | 2167.9 | 4461.7 | -0.01 | -0.01 | #N/A | #N/A | #N/A | #N/A | -0.28 | -0.03 |
| BH107B | 2167.9 | 4501.7 | -0.03 | -0.04 | -0.08 | -0.08 | -0.01 | 0.00 | -0.30 | -0.03 |
| BH108A | 2167.9 | 3711.7 | -0.05 | -0.06 | -0.08 | -0.08 | 0.00 | 0.00 | -0.35 | -0.036 |
| BH108B | 2167.9 | 3751.7 | -0.02 | -0.02 | -0.11 | -0.11 | 0.00 | -0.32 | -0.32 | -0.03 |
| BH109A | 2167.9 | 2961.7 | -0.02 | -0.02 | -0.10 | -0.10 | 0.00 | -0.34 | -0.34 | -0.03 |
| BH109B | 2167.9 | 3001.7 | -0.05 | -0.07 | -0.08 | -0.08 | 0.00 | -0.35 | -0.35 | -0.04 |
| BH110A | 2167.9 | 2211.7 | -0.02 | -0.02 | -0.10 | -0.10 | 0.00 | -0.32 | -0.32 | -0.03 |
| BH110B | 2167.9 | 2251.7 | -0.04 | -0.05 | -0.08 | -0.08 | -0.01 | -0.37 | -0.37 | -0.04 |
| BH111A | 1518.8 | 4876.1 | 0.02 | 0.03 | -0.10 | -0.10 | -0.02 | -0.29 | -0.29 | -0.03 |
| BH111B | 1518.6 | 4835.8 | 0.03 | 0.04 | -0.11 | -0.11 | -0.02 | -0.29 | -0.29 | -0.03 |
| BH112A | 1518.6 | 4126.1 | 0.01 | 0.01 | -0.10 | -0.10 | -0.02 | -0.34 | -0.34 | -0.03 |
| BH112B | 1518.3 | 4086.0 | 0.01 | 0.01 | -0.11 | -0.11 | -0.02 | -0.34 | -0.34 | -0.03 |
| BH113A | 1518.9 | 3376.3 | -0.02 | -0.02 | -0.09 | -0.09 | -0.01 | -0.36 | -0.36 | -0.04 |
| BH113B | 1518.7 | 3335.8 | -0.02 | -0.02 | -0.09 | -0.09 | -0.01 | -0.36 | -0.36 | -0.04 |
| BH114A | 1518.9 | 2625.6 | -0.03 | -0.04 | -0.09 | -0.09 | 0.00 | -0.37 | -0.37 | -0.04 |
| BH114B | 1518.8 | 2586.3 | -0.04 | -0.06 | -0.09 | -0.09 | 0.00 | -0.34 | -0.34 | -0.03 |

Appendix 3

Fitting Parameters for Long Term Subsidence Prediction

| | NORTH | EAST | Y_0 | A_1 | t_1 |
|--------|--------|--------|----------|----------|------------|
| 5 | 2410.7 | 2154.8 | 94.33045 | 0.39613 | 64.21564 |
| 6 | 3086.2 | 3516.4 | 89.96714 | 6.93767 | 3255.28676 |
| 7 | 3086.0 | 4486.4 | | | |
| 8 | 3085.1 | 2936.0 | | | |
| 9 | 1273.4 | 4256.3 | 84.8699 | 0.44907 | 46.94525 |
| 10 | 1273.3 | 3216.3 | 87.69877 | 0.46422 | 48.52785 |
| 11A | 2187.0 | 6003.5 | | | |
| 12 | 1790.0 | 4814.7 | | | |
| 13 | 2175.8 | 3242.2 | 92.40316 | 0.26364 | 29.68799 |
| 14 | 2213.9 | 3968.4 | 91.37891 | 0.33274 | 52.14162 |
| BH101A | 2817.0 | 5587.6 | 94.11908 | 0.13249 | 38.51311 |
| BH101B | 2817.1 | 5627.3 | 94.06028 | 0.12386 | 35.54321 |
| BH102A | 2816.8 | 4837.0 | 95.513 | 0.21547 | 42.84765 |
| BH102B | 2816.8 | 4877.0 | 95.46468 | 0.21469 | 44.26207 |
| BH103A | 2817.0 | 4087.0 | 95.85721 | 0.029095 | 53.87395 |
| BH103B | 2817.0 | 4127.3 | 95.8312 | 0.31899 | 66.44405 |
| BH104A | 2816.9 | 3337.4 | 96.66862 | 0.34481 | 48.74488 |
| BH104B | 2816.4 | 3377.4 | 96.76657 | 0.36303 | 56.19501 |
| BH105A | 2816.8 | 2587.4 | 98.33347 | 0.32064 | 43.71217 |
| BH105B | 2816.9 | 2626.9 | 98.35462 | 0.31593 | 42.37535 |
| BH106A | 2167.9 | 5211.9 | 91.01704 | 0.19381 | 36.21939 |
| BH106B | 2167.9 | 5251.7 | 91.01422 | 0.21704 | 38.58779 |
| BH107A | 2167.9 | 4461.7 | 97.41315 | 0.25287 | 33.42865 |
| BH107B | 2167.9 | 4501.7 | 97.33787 | 0.31462 | 52.84372 |
| BH108A | 2167.9 | 3711.7 | 94.3362 | 0.35177 | 41.43518 |
| BH108B | 2167.9 | 3751.7 | 94.32835 | 0.35544 | 52.81414 |
| BH109A | 2167.9 | 2961.7 | 96.22047 | 0.36533 | 48.92786 |
| BH109B | 2167.9 | 3001.7 | 96.28395 | 0.36491 | 48.62465 |
| BH110A | 2167.9 | 2211.7 | 95.75876 | 0.37243 | 65.69522 |
| BH110B | 2167.9 | 2251.7 | 95.77493 | 0.38158 | 46.3358 |
| BH111A | 1518.8 | 4876.1 | 90.90043 | 0.26402 | 46.38014 |
| BH111B | 1518.6 | 4835.8 | 90.94044 | 0.29334 | 54.13512 |
| BH112A | 1518.6 | 4126.1 | 91.32225 | 0.35743 | 54.37363 |
| BH112B | 1518.3 | 4086.0 | 91.3363 | 0.35225 | 54.14484 |
| BH113A | 1518.9 | 3376.3 | 91.78928 | 0.38197 | 57.28376 |
| BH113B | 1518.7 | 3335.8 | 91.71134 | 0.39437 | 56.10384 |
| BH114A | 1518.9 | 2625.6 | 87.97098 | 0.38767 | 52.94901 |
| BH114B | 1518.8 | 2586.3 | 88.13465 | 0.38448 | 63.792 |

*The fitting parameter x_0 (x_1 at time =0) is equal to zero for all predictions.

DISTRIBUTION

| | |
|--|---|
| U.S. Department of Energy (2) Strategic Petroleum Reserve 1000 Independence Avenue SW Washington, D.C. 20585 <u>Attn:</u> D. Johnson, FE 421 D. Buck, FE 421 | <u>Sandia Internal:</u> (20) MS 0701 L. Shephard, 6100 MS 0706 J. Linn, 6113 MS 0706 B. Ehgartner, 6113 MS 0706 T. Hinkebein, 6113 MS 0706 D. Munson, 6113 MS 0706 C. Williams, 6113 MS 0706 S. Bauer, 6113 (10) MS 9018 Cen. Tech. Files, 8940-2 MS 0899 Tech. Library, 4916 (2) MS 0619 Review and Approval Desk for DOE/OSTI, 15102 |
| U.S. Department of Energy (13) Strategic Petroleum Reserve 900 Commerce Road East New Orleans, LA 70123 <u>Attn:</u> W. C. Gibson, FE 44 J. C. Kilroy, FE 443 W. Poarch, FE 4432 G.B. Berndsen, FE 443.1 (5) J. Culbert, FE 443 R. Myers, FE 4421 TDCS (2) | |
| U.S. Department of Energy (3) Strategic Petroleum Reserve <u>Attn:</u> A. Fruge, DOE SPR Big Hill (3) | |
| DynMcDermott (4) 850 South Clearview Parkway New Orleans, LA 70123 <u>Attn:</u> L. Eldredge, EF 20 K. Mills, EF 20 J. McHenry, EF 25 | |
| PB-KBB Inc. 11767 Katy Freeway P O Box 19672 Houston, TX 77224 <u>Attn:</u> S. Raghuraman | |